

Electrical Signature Analysis (ESA) as a Diagnostic Maintenance Technique for Detecting the High Consequence Fuel Pump Failure Modes

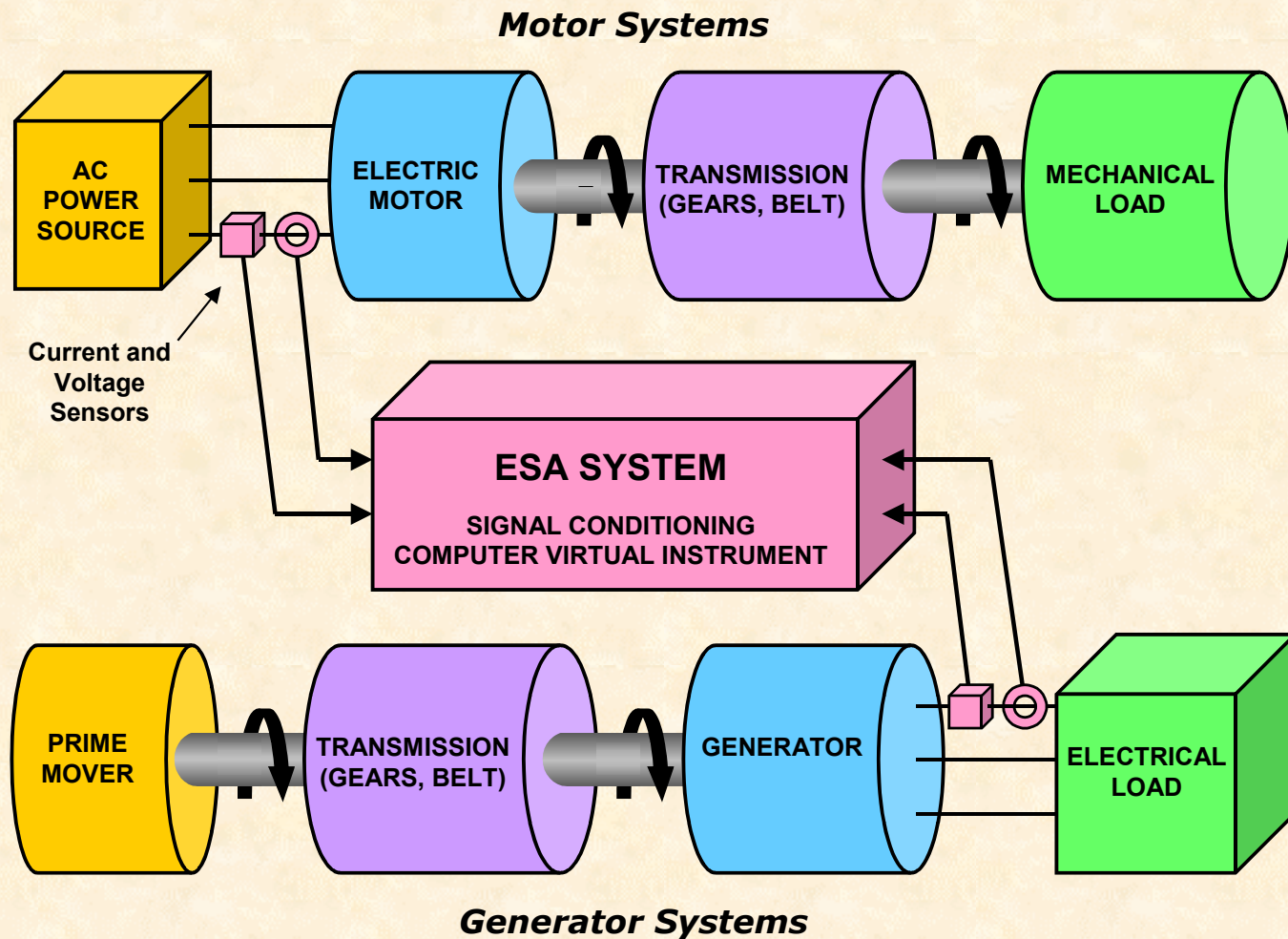
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This presentation will show how electrical signature analysis (ESA) methods can be used to monitor the condition of fuel pumps and other electromechanical devices

- **BACKGROUND**
 - **Basic Principle**
 - **General Benefits**
 - **Application Examples**
 - **Acceptance of ESA Technology**
- **CONDITION MONITORING OF C-141 FUEL PUMPS**
 - **General Information**
 - **Portable System**
 - **Test Locations**
 - **Data Analysis** (*time waveforms, frequency spectra, key parameters*)
 - **Detecting Fuel Pump Degradation with ESA** (*bearing wear*)
- **ONGOING WORK**
- **SUMMARY**

ESA capitalizes on the intrinsic abilities of conventional electric motors and generators to act as transducers and only requires access to the equipment electrical lines



ESA is an attractive technology for a wide variety of applications

BENEFITS	<ul style="list-style-type: none">• Non-intrusive and remote monitoring capability• No equipment-mounted sensors required• Applicable to high and low power equipment• Large range of applicable analysis methods• High sensitivity to a variety of disorders<ul style="list-style-type: none">– degraded & misaligned motors and generators– worn bearings, gears, and belts– unstable process conditions– power system degradation
WHEN TO USE ESA	<ul style="list-style-type: none">• On-line performance monitoring• Catastrophic failure prevention• Improved safety, reliability, and operational readiness• Quality assurance and evaluation• Energy conservation• Predictive maintenance (prognostics)• Field diagnostic testing• Remaining life assessments

ESA has been used on a large number of components and systems

◆ Fuel Injectors and Solenoid Valves

- Army Portable Power Generator-Sets
- Heat Pump and Air Conditioning Systems
- NASA Propellant Control Valve

◆ Consumer Power Tools and Appliances

- Army Ammunition Delivery Systems
- Multi-Axis Industrial Cutting Machines
- Electric Vehicle Motors and Alternators

◆ Aircraft Integrated Drive Generators

- Navy Fire and Seawater Pumps
- Other Centrifugal Water Pumps
- Reproduction Machine Motors

◆ Vacuum Pumps

- Nylon Spinning Machines

◆ Peristaltic Pumps

- Diesel Engine Starter Motors

◆ Motor-Operated Valves

- Large Blowers and Fans

◆ Aircraft Fuel Pumps

- Coal Pulverizers

◆ Large Compressors

- Variable Speed Motors

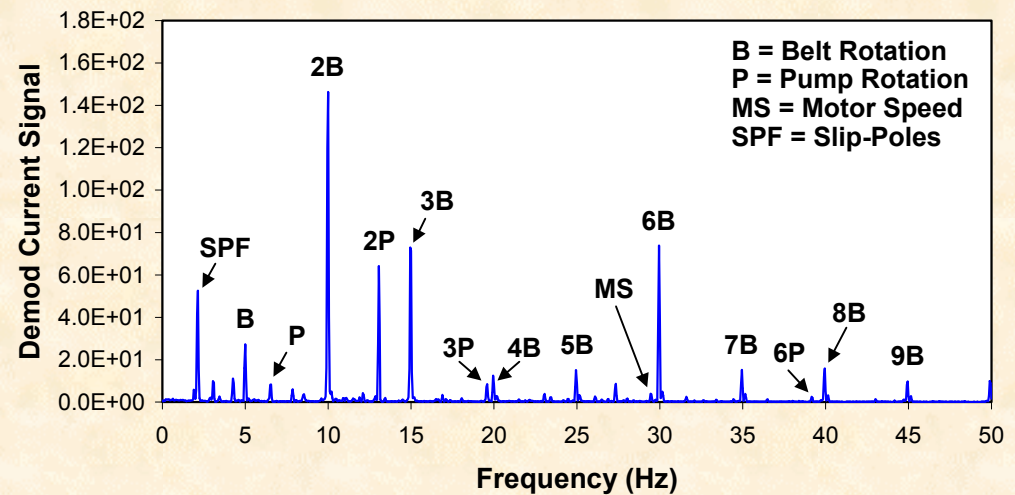
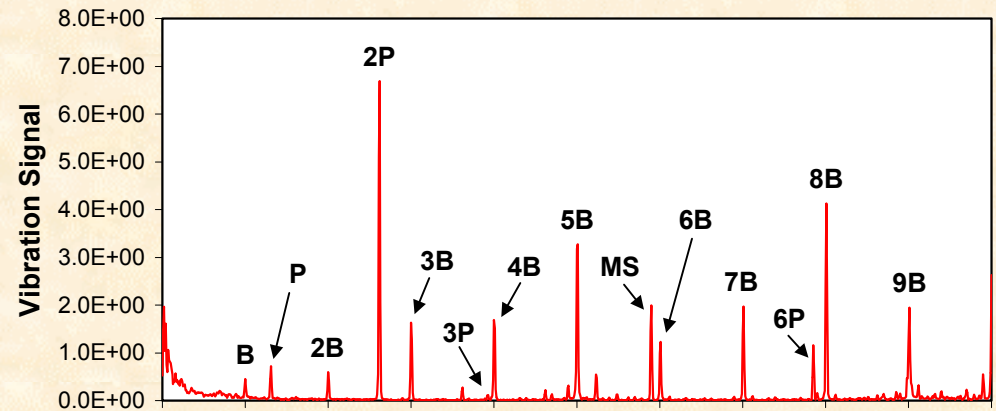
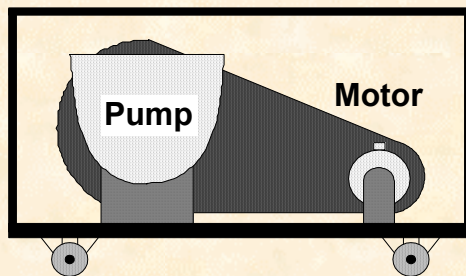
◆ Helicopters

◆ *examples provided in this presentation*

Using ESA, motors and generators act like accelerometers that are already installed and sending signals along the power line

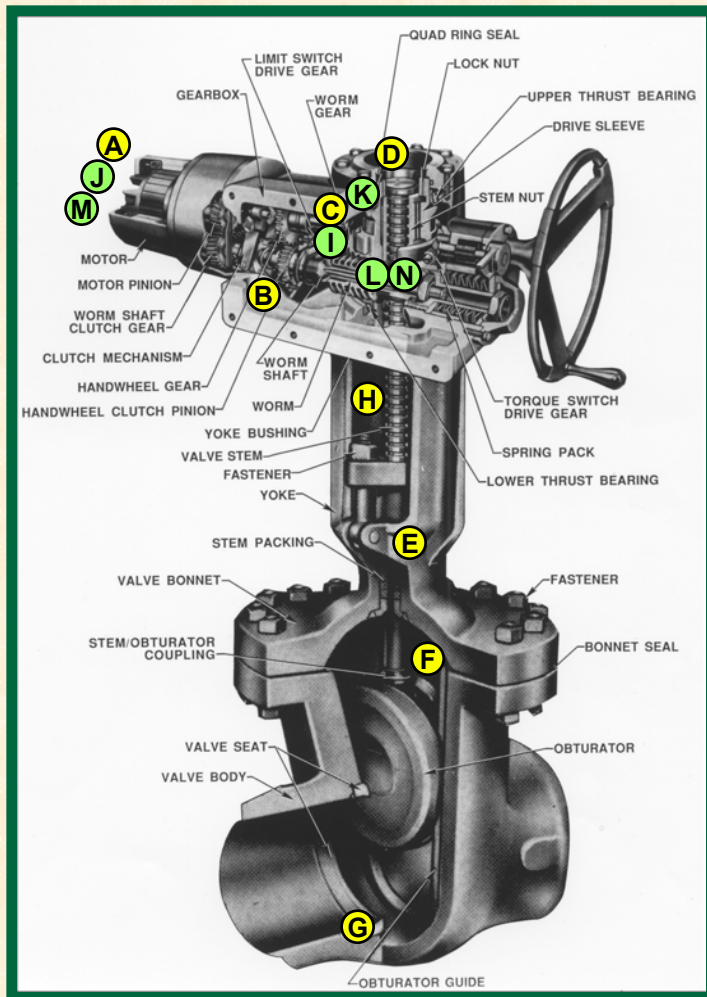
(Example: Vacuum Pump)

- Periodic mechanical events associated with the motor, belt, and pump produce periodic vibrations and periodic variations in running current.
- All key mechanical events are sensed by both the accelerometer and motor.

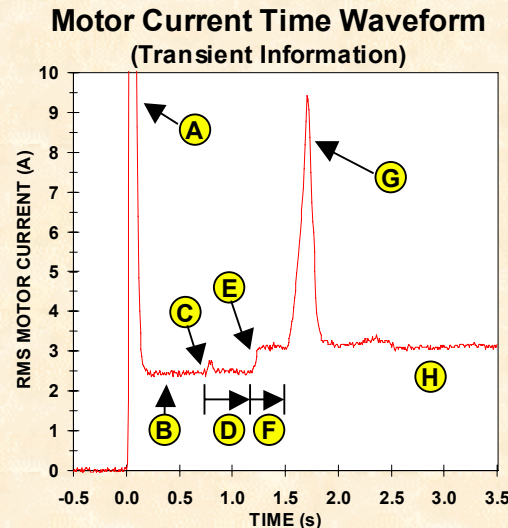


ESA can reveal detailed information at the subcomponent level

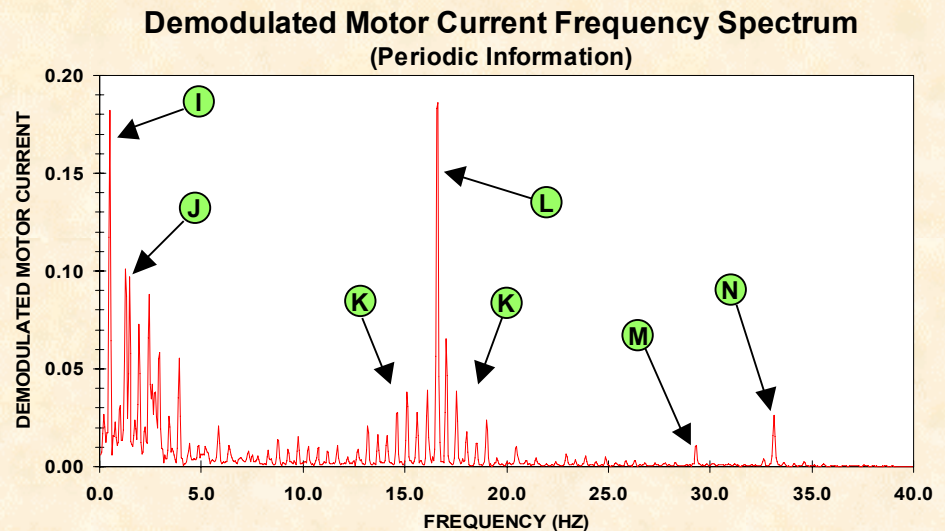
(Example: Motor-Operated Valve)



Motor-Operated Valve

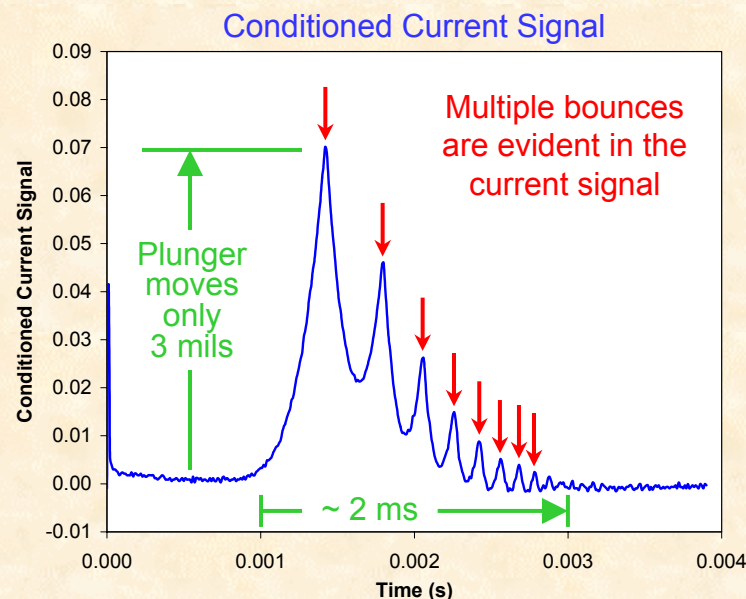
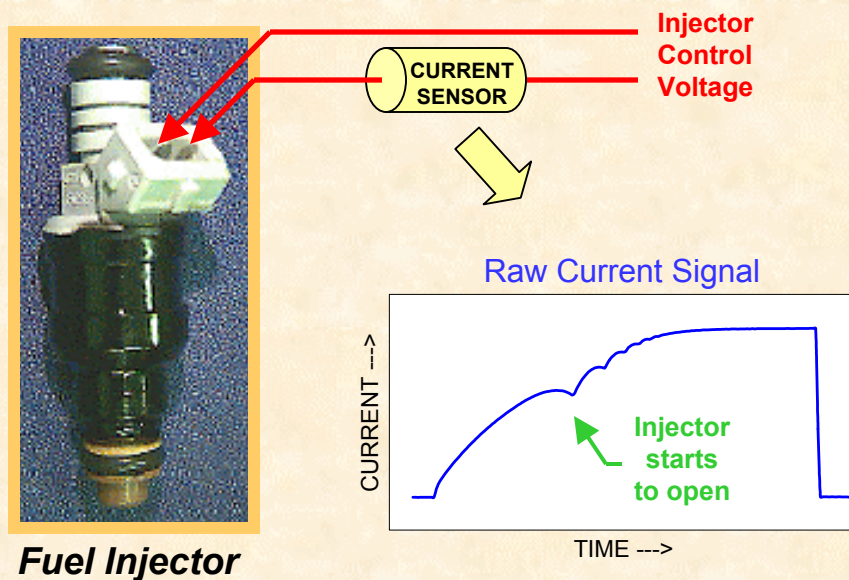


- A** Motor inrush current
- B** No-load current
- C** Hammerblow current
- D** Stem nut clearance time
- E** Packing drag current
- F** Stem coupling time
- G** Unseating current
- H** Total running current
- I** Worm gear rotation
- J** Motor slip
- K** Worm gear rotation sidebands
- L** Worm gear tooth meshing
- M** Motor speed
- N** Worm gear mesh harmonic



The feasibility of using ESA to monitor the performance and condition of fuel injectors has been demonstrated

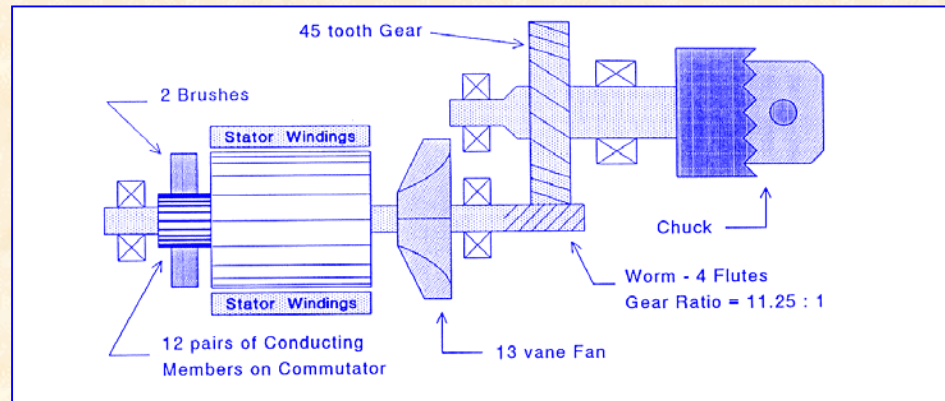
- ESA methods can differentiate between effects due to changes in injector temperature, voltage, and supply pressure.
- ESA methods have been successful at detecting injector outlet port plugging.
- ESA offers a quick, inexpensive method for checking the quality of newly-manufactured injectors.
- ESA can be the basis for new, non-intrusive test equipment for engine maintenance shops.



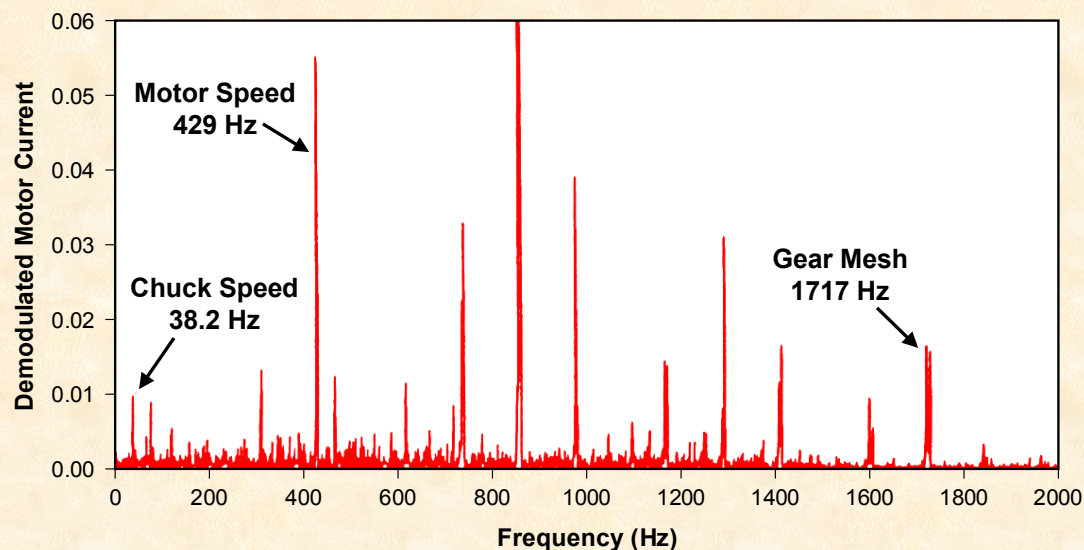
Several consumer tools and appliances were also examined to show the versatility of ESA

(Example: Power Drill)

- Drill frequency components were observed with ESA.
- Relationships were established between vibration magnitudes and ESA parameters for different levels of motor unbalance.

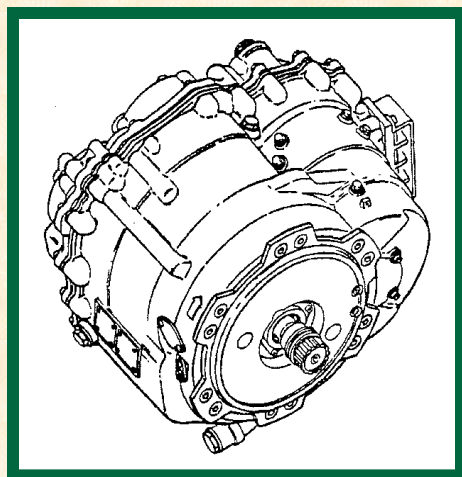


Power Drill

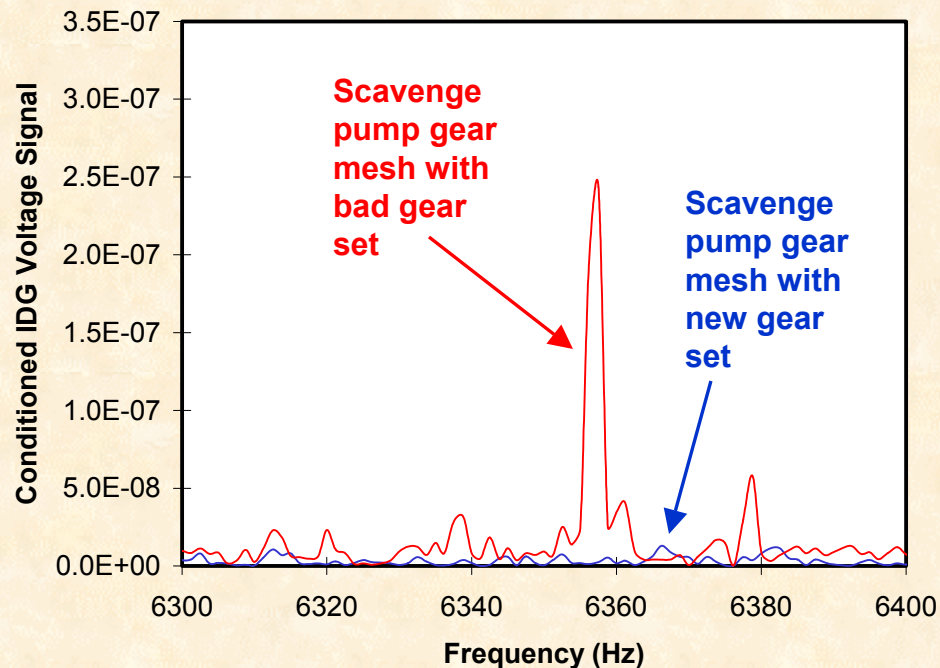


ESA was used to detect mechanical degradation on a commercial aircraft integrated drive generator (IDG)

- IDGs provide power for devices in the passenger cabin such as reading lights and microwave ovens.
- On certain aircraft, IDGs fail at the rate of four per year. Each IDG costs \$250K to replace.
- The primary failure mode is seizure and destruction of scavenge, drive pump, and axial gears on the IDG's main shaft.
- Even at very low generator electrical loads, ESA can detect gear problems before they fail.

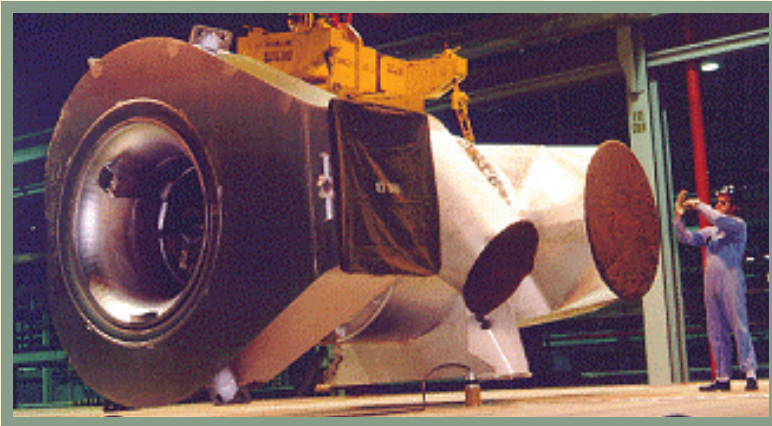


*Integrated Drive
Generator (IDG)*

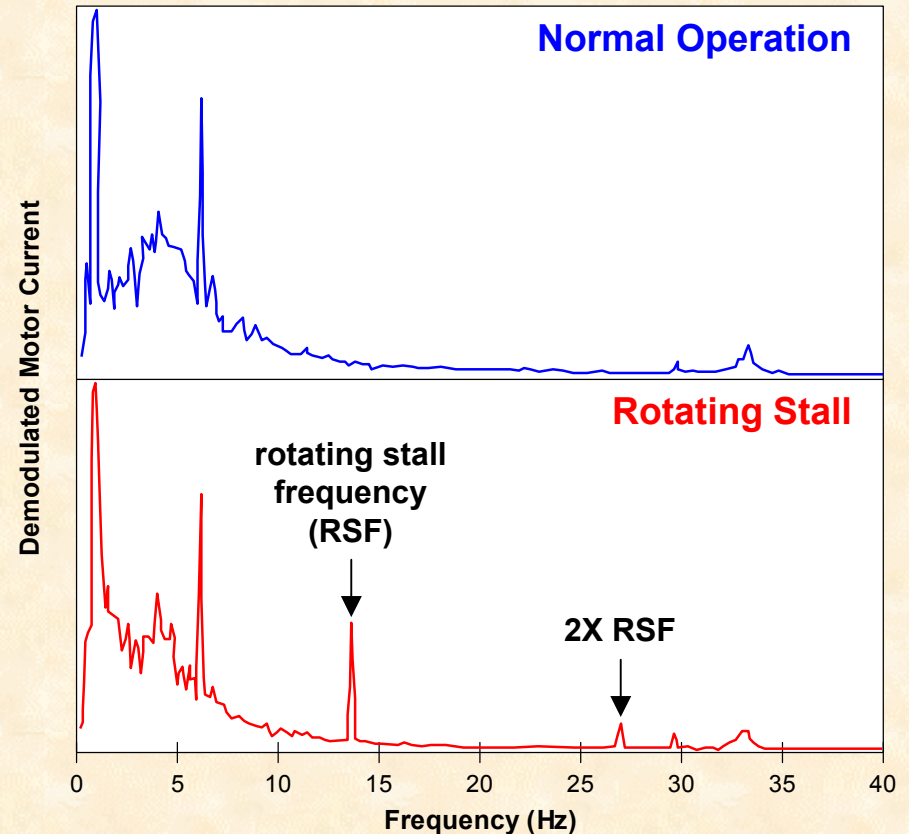


Damaging aerodynamic conditions, such as rotating stall, can be detected using ESA

- 1700-hp axial flow compressors are used in large numbers in U.S. uranium enrichment plants.
- Certain process flow configurations can induce rotating stall, which quickly accelerates blade fatigue damage.



1700-hp Axial-Flow Compressor

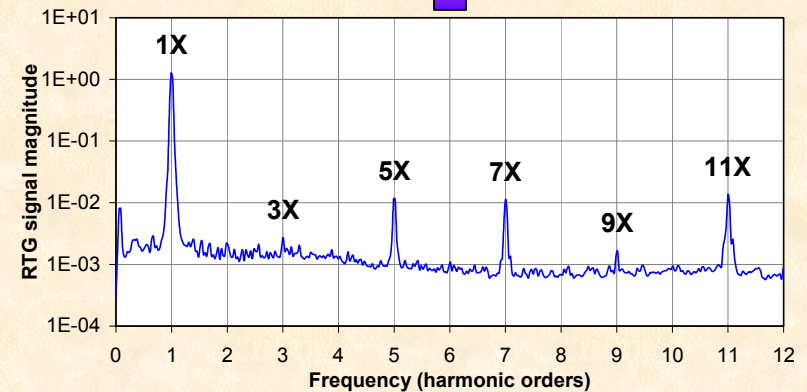
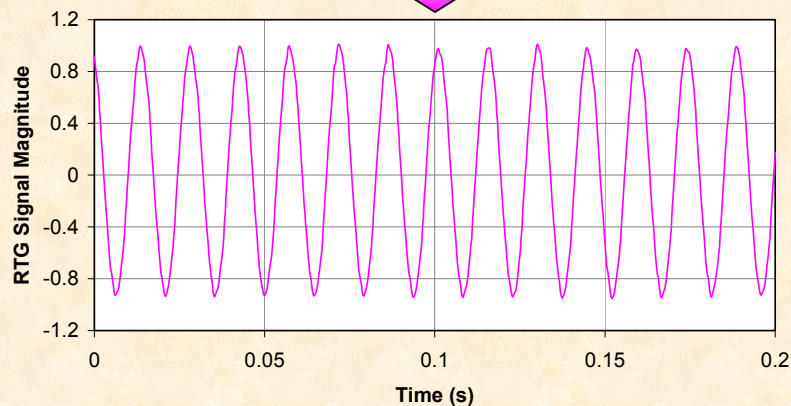
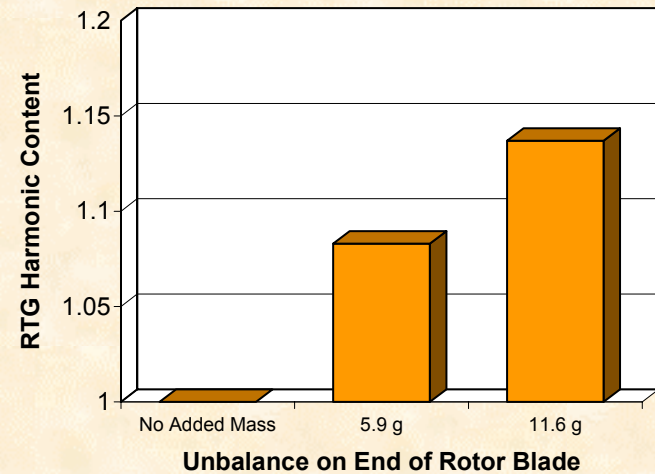


*Demodulated Motor Current Spectra
Obtained From the Control Room*

A relationship was identified between helicopter rotor unbalance and the harmonic content of the rotor tachometer generator (RTG) output voltage

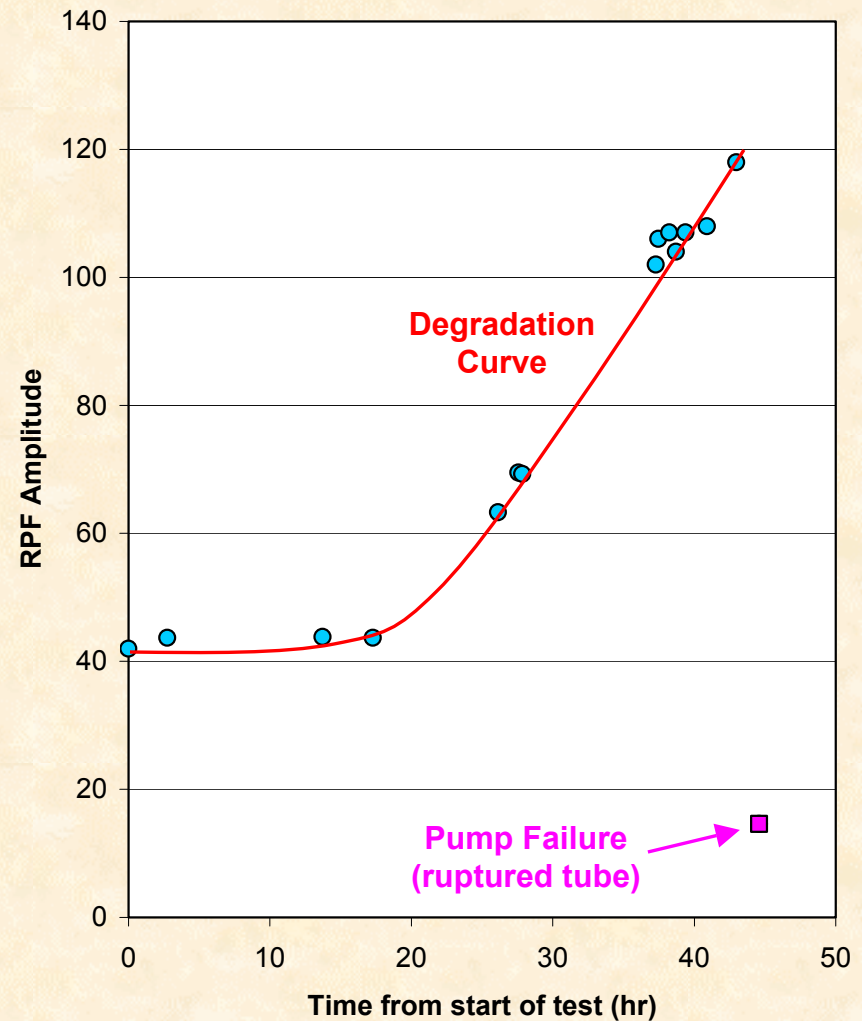
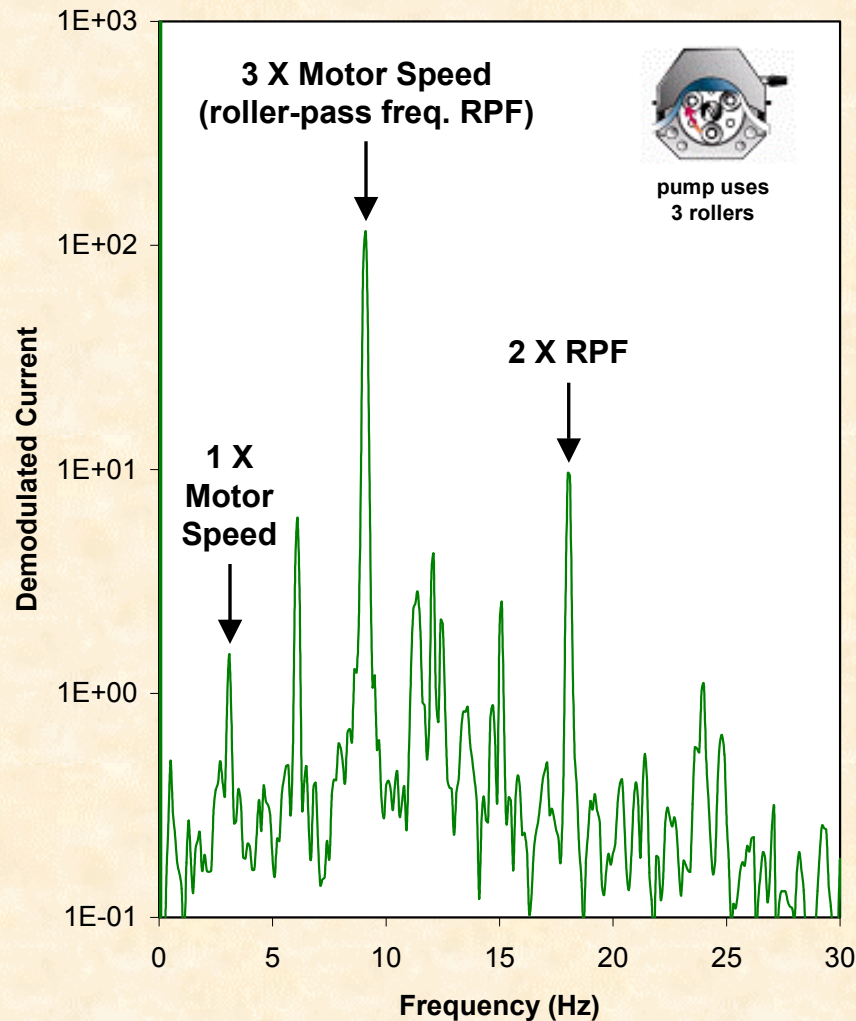


Bell Jet Ranger Helicopter

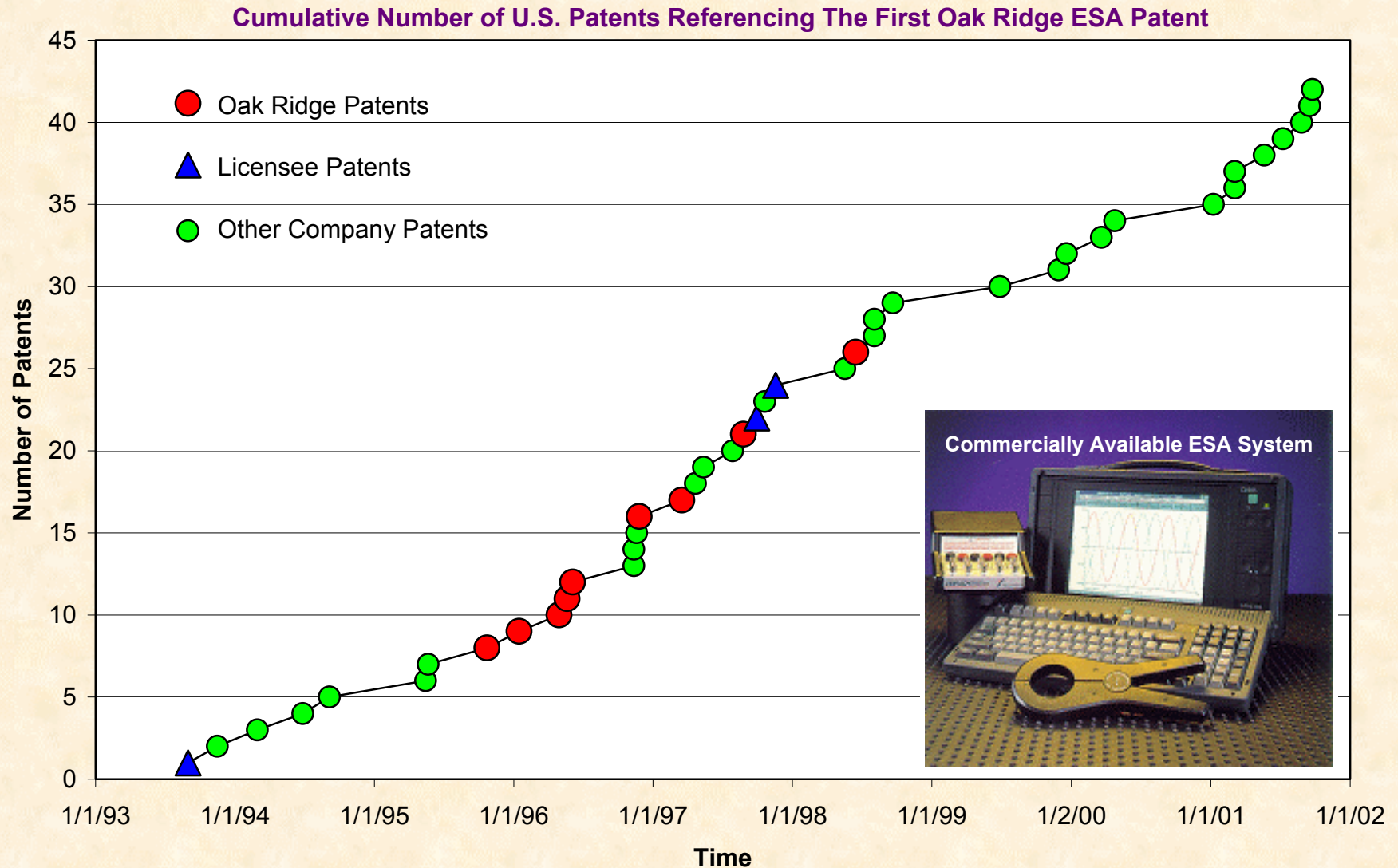


ESA can detect changes in component condition before failure

(Example: Peristaltic Pump)



ESA is now recognized as a viable diagnostic method

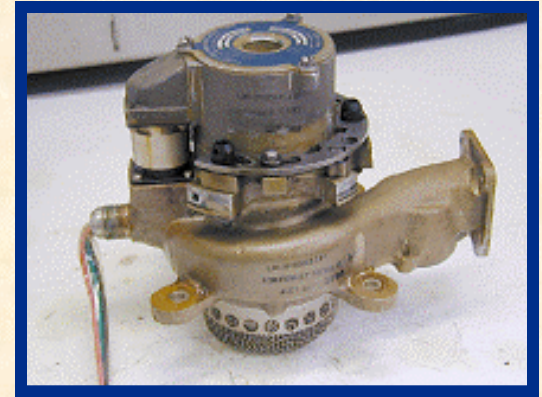


ORNL is presently developing an ESA-based instrument for monitoring the condition of C-141 fuel booster pumps

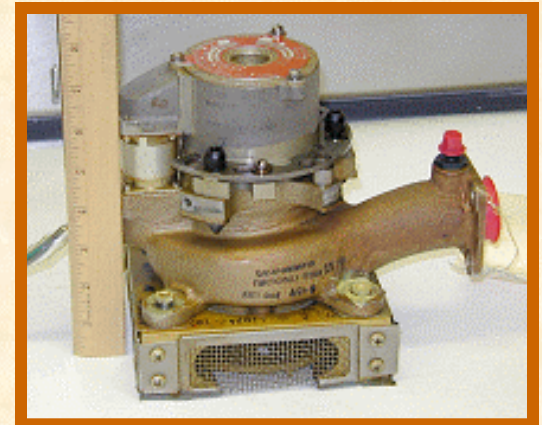


C-141 Starlifter

- Each C-141 has 20 fuel booster pumps (5 fuel tanks per wing, 2 pumps per tank)
- Fuel pumps are centrifugal and driven by 3-phase electric motors
- Two designs are used: Main (~ 4A), Aux (~ 10A)
- Work to date has focused on the aux fuel pump

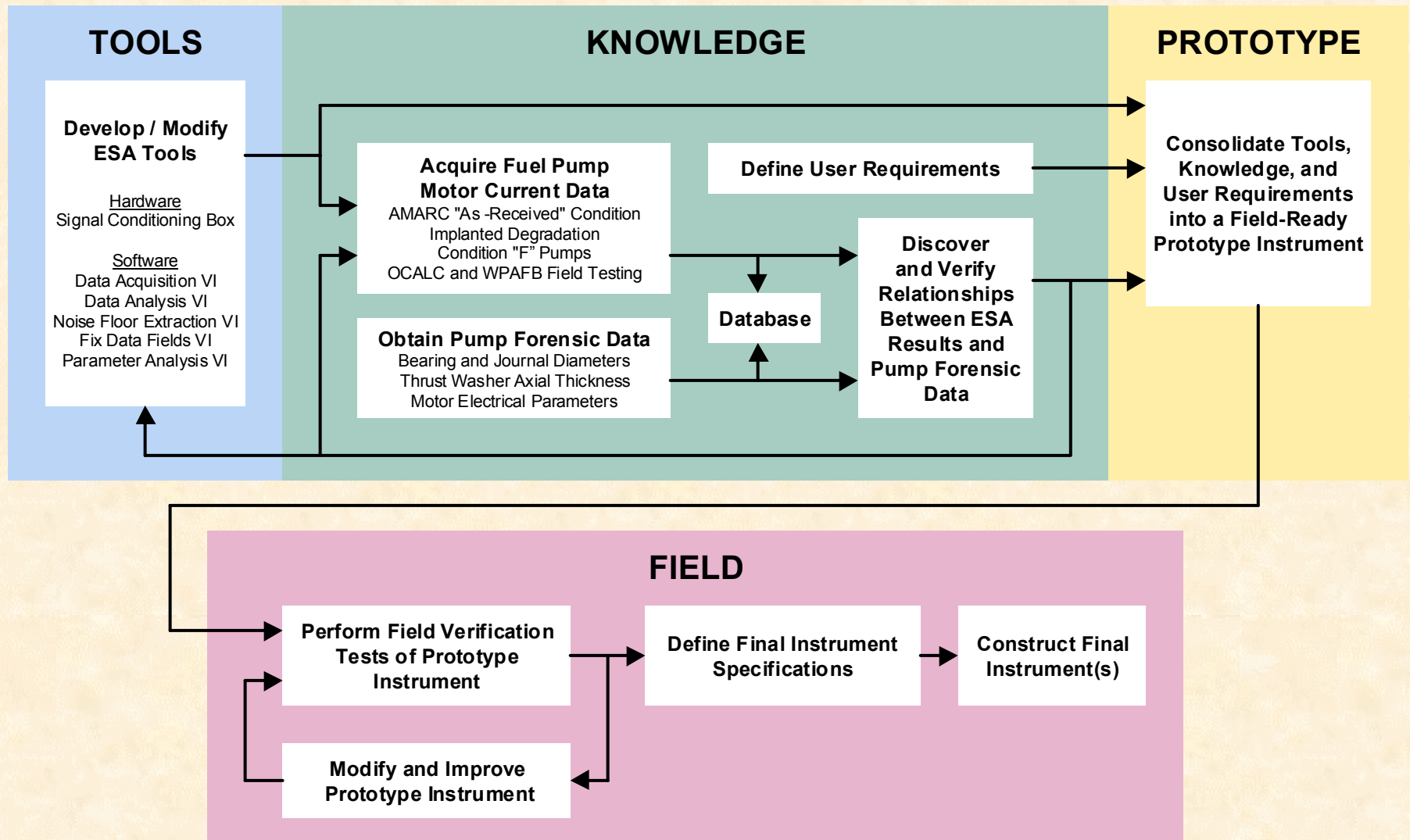


Main Fuel Pump



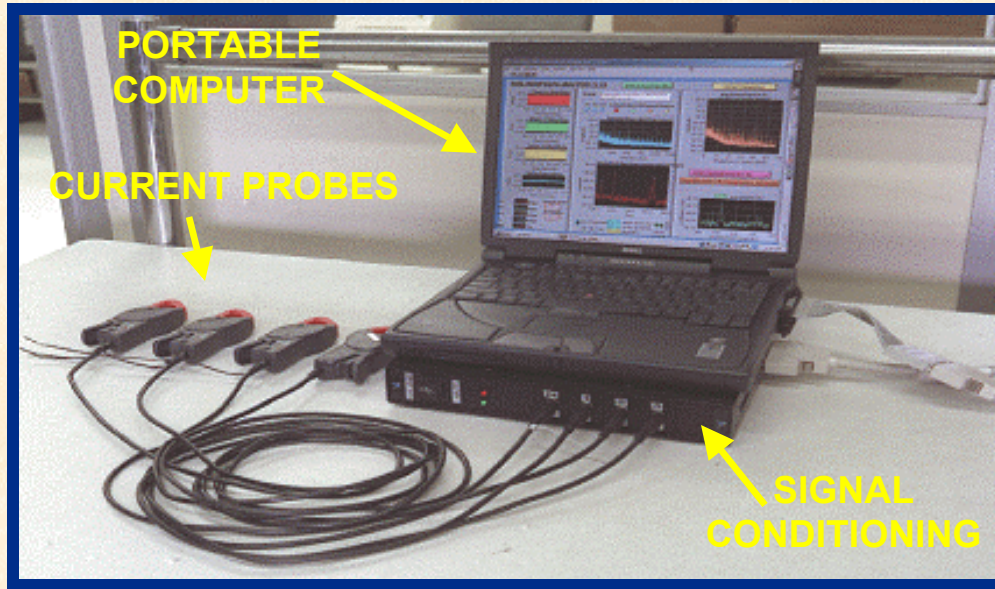
Auxiliary Fuel Pump

The development is progressing well and is being accomplished through a series of tasks



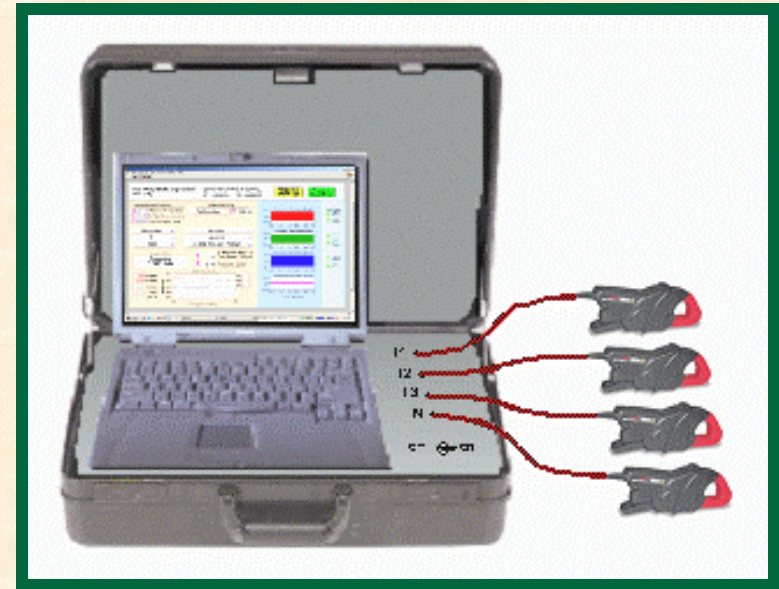
Fuel pump motor current signals have been obtained using a portable system

Present System



Fuel pump data acquisition system developed as a research and development tool

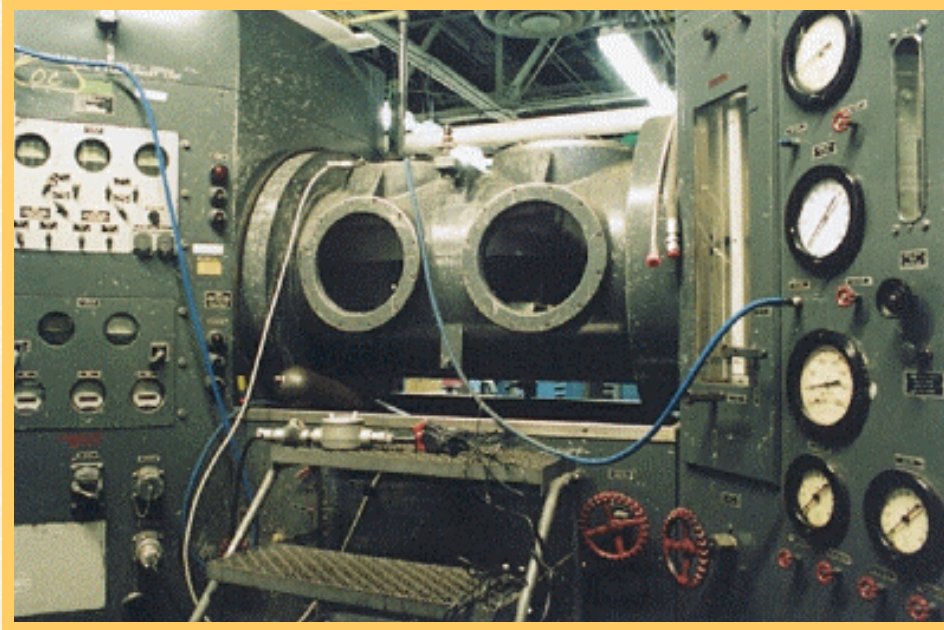
System Under Development



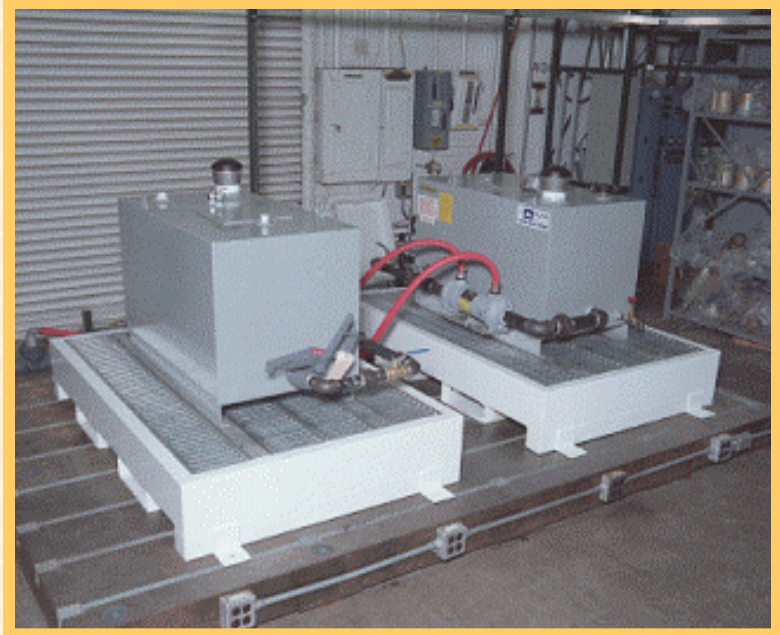
Concept of a "suitcase-style" ESA-based diagnostic system

The suitcase-style ESA system can serve as the platform for other potential aircraft diagnostic applications such as flight control surface drive actuators, landing gear bay door actuators, integrated drive generators, etc.

Fuel pumps have been tested at two test facilities



***Oklahoma City Air Logistics Center
(OC-ALC) Fuel Pump Test Facility***



ORNL Fuel Pump Test Facility

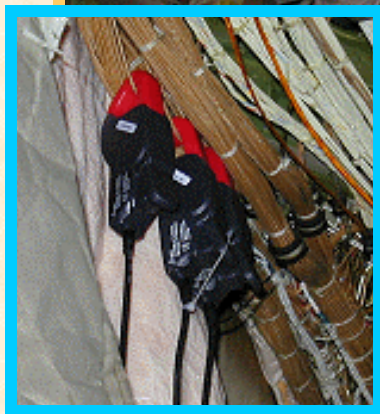
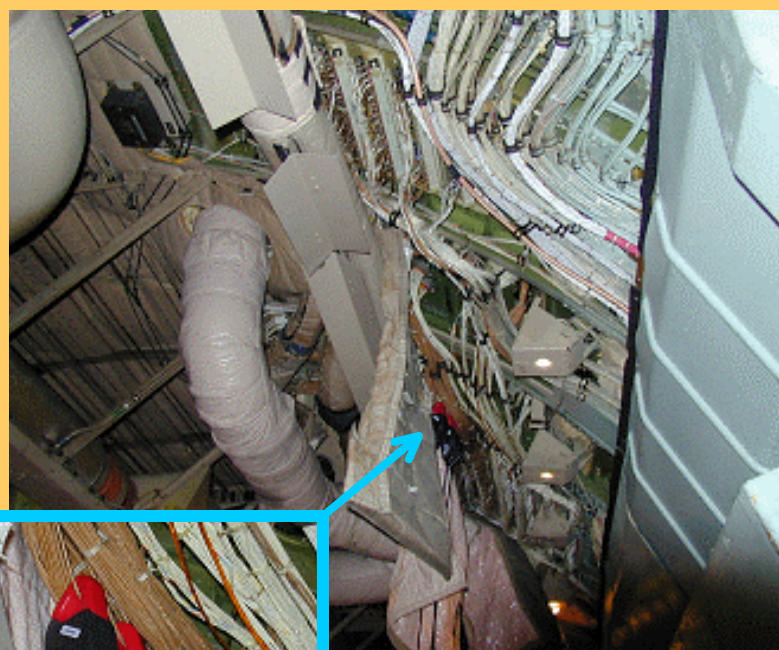
Fuel pumps have also been tested on four C-141 aircraft at Wright-Patterson Air Force Base

(Tail Numbers: 67959, 50249, 60132, 67957)

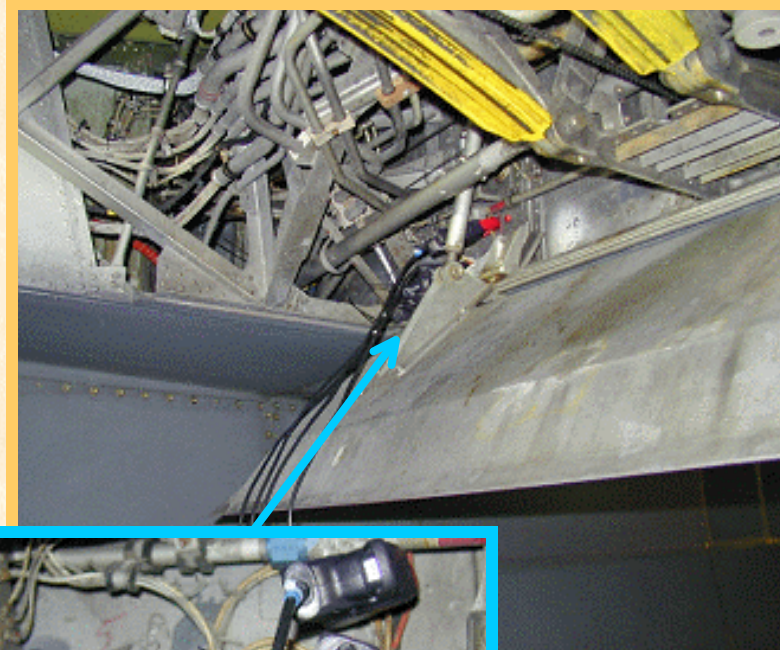


Fuel pump motor current leads are accessible at several locations on the C-141

Inside Fuselage



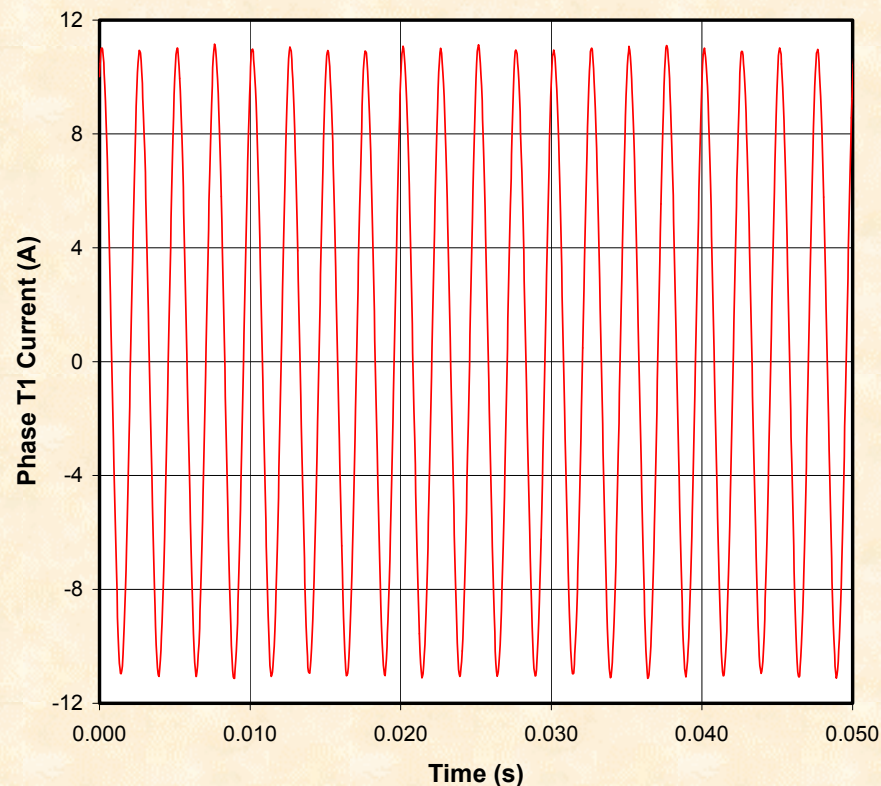
Under Wing



Software was developed to acquire and save fuel pump current waveforms for off-line analysis



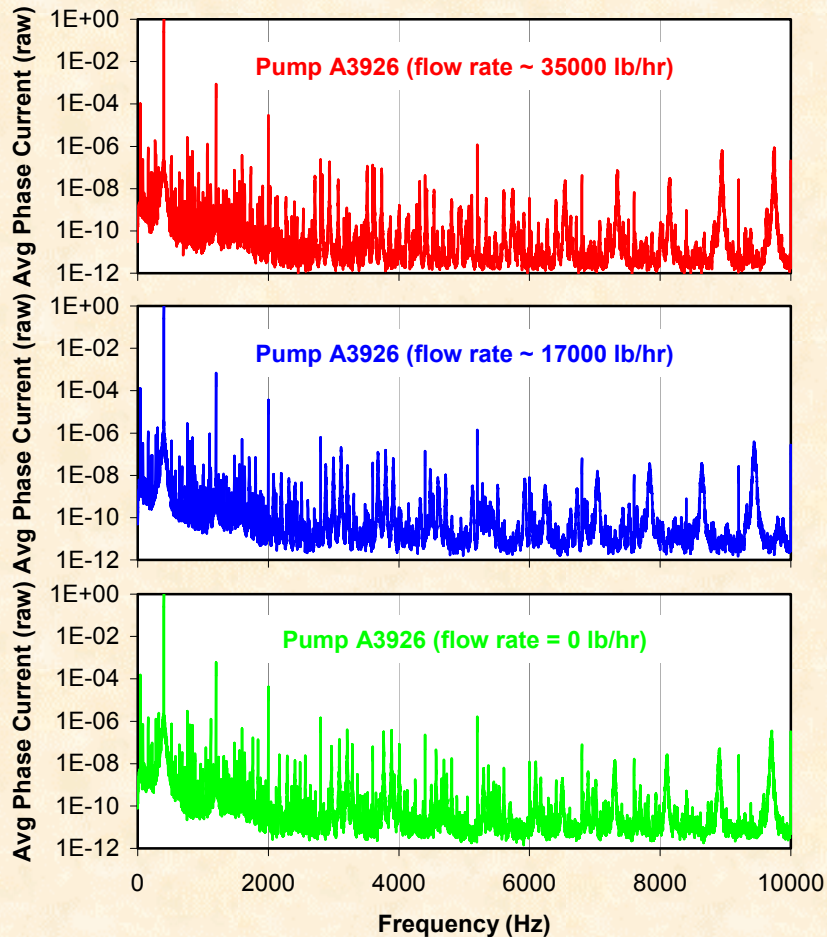
***Portable Computer and Data Acquisition
Virtual Instrument (VI)***



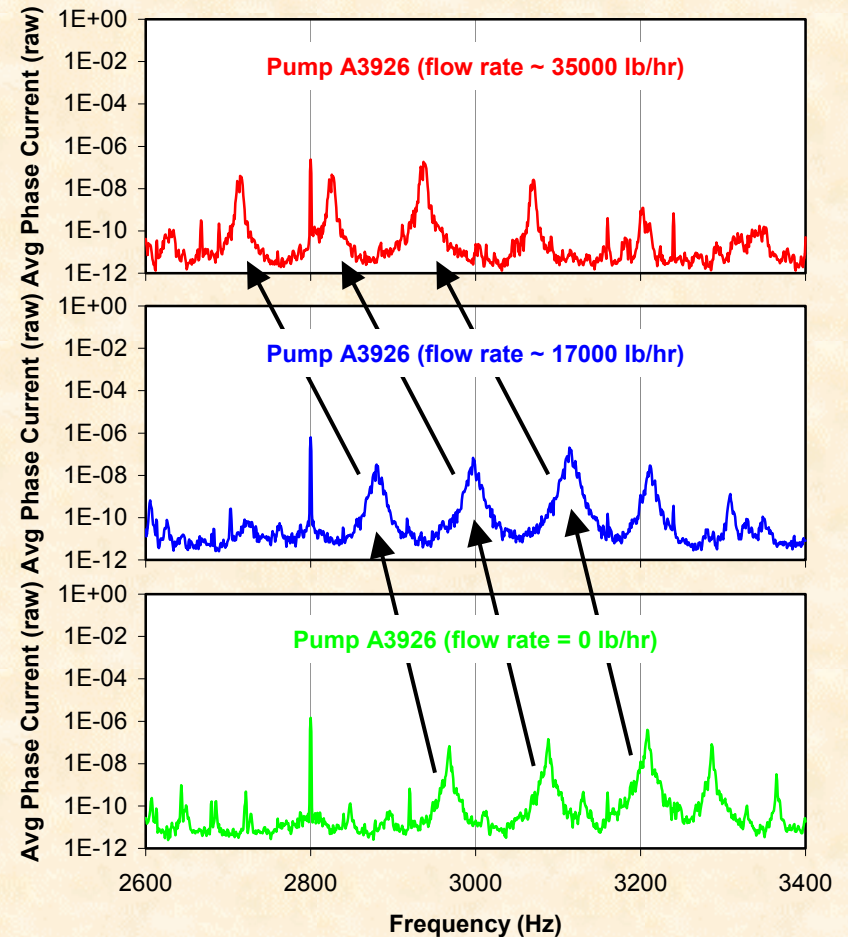
***Typical Single Phase
Current Waveform***

Auxiliary fuel pump motor current spectra are complex and difficult to analyze in their “raw” state

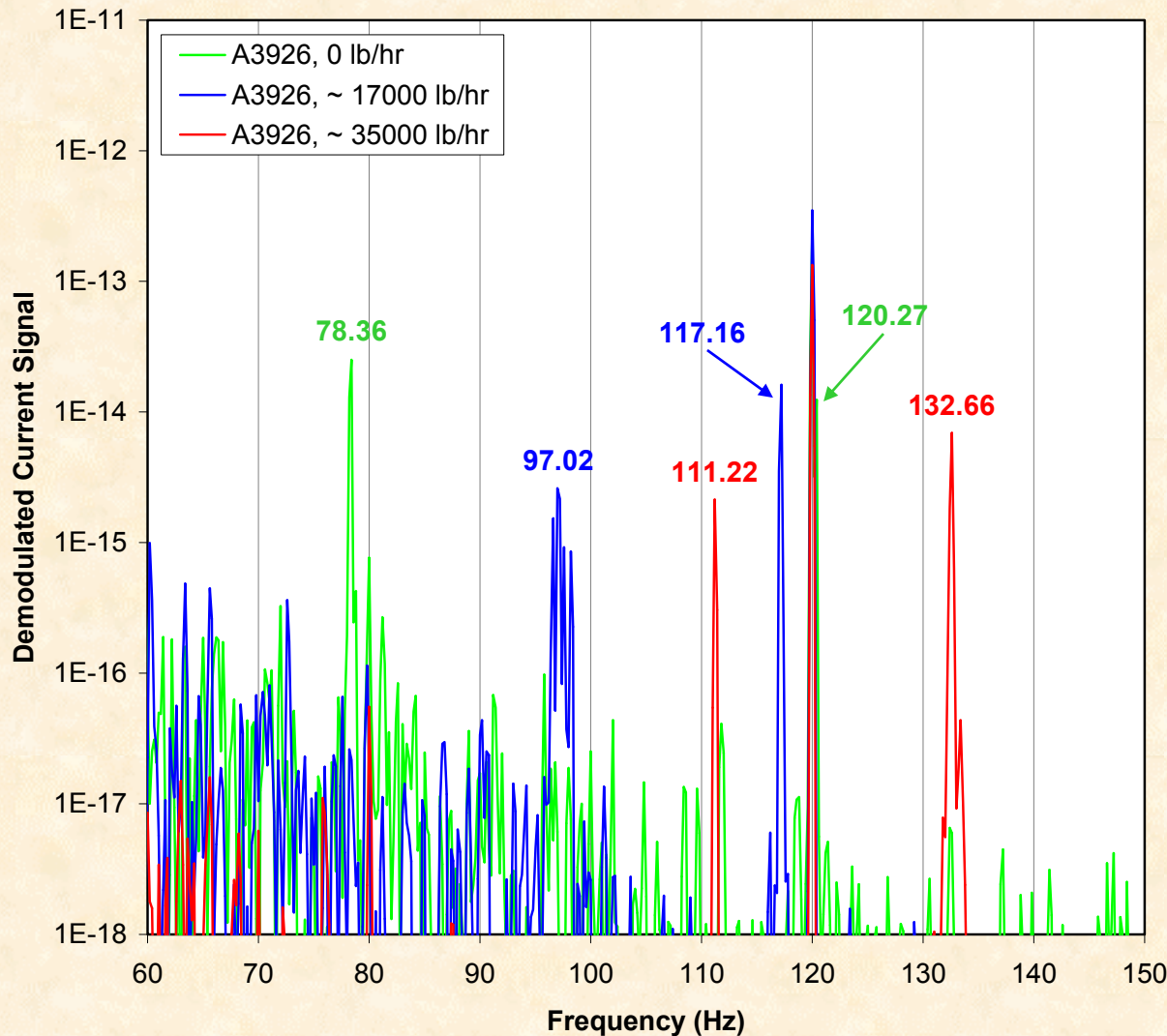
Many Frequency Components Are Present



Most Peaks Move As Flow Rate Changes



By demodulating the raw current signals, the motor speed peaks can be identified and the rest of the spectrum more easily interpreted



$$SS = 2 (LF) / NP$$

$$SPF = NP (SS - MS)$$

MS = motor speed (Hz)
LF = line frequency (Hz)
NP = number of motor poles
SS = synchronous speed (Hz)
SPF = slip pole frequency (Hz)

For An Auxiliary Fuel Pump

NP = 6; LF = 400 Hz
SS = 2 (400 Hz) / 6 = 133.33 Hz

at 0 lb/hr:

MS = 120.27 Hz (7216.2 RPM)
SPF = 78.36 Hz

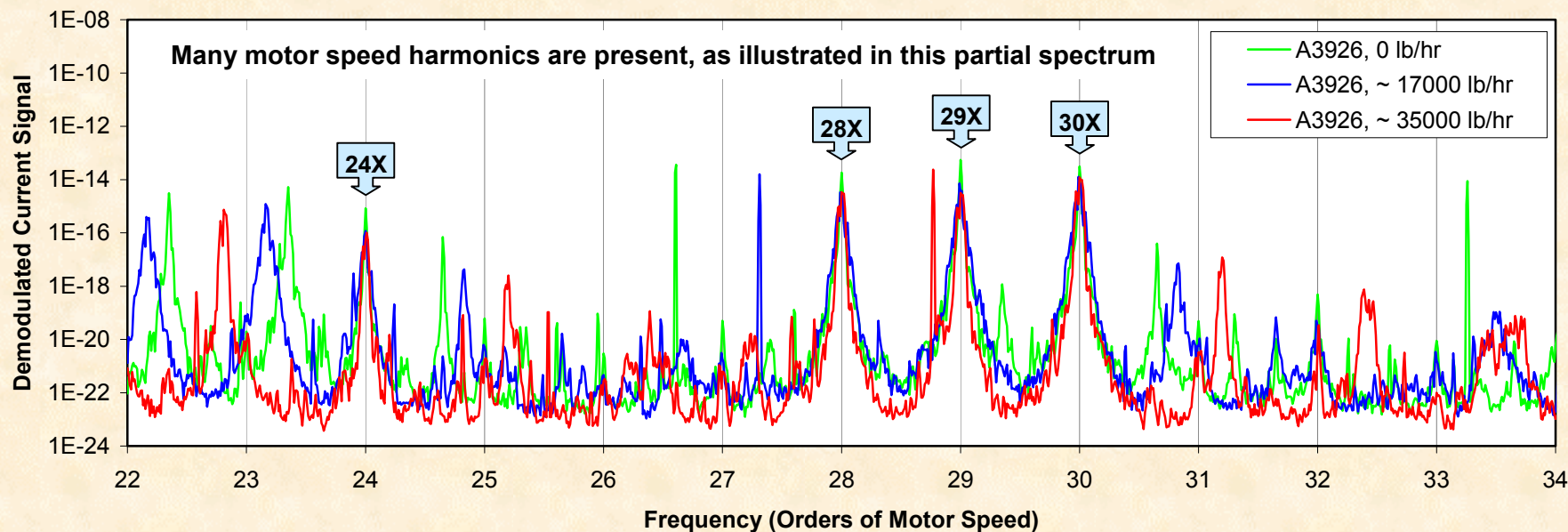
at 17000 lb/hr:

MS = 117.16 Hz (7029.6 RPM)
SPF = 97.02 Hz

at 35000 lb/hr:

MS = 111.22 Hz (6673.2 RPM)
SPF = 132.66 Hz

Demodulated motor current spectra can then be analyzed on a relative frequency scale (orders of motor speed)



ESA Parameter	Relationship With Auxiliary Pump And Motor Design
1xMS, 2xMS	Fundamental and second harmonic of motor speed.
motor slip-poles	The magnitude of the slip-poles peak increases with motor rotor bar degradation.
4xMS	The pump has 4 impeller vanes.
6xMS, 12xMS, 18xMS, 24xMS, 30xMS, 36xMS	These harmonics represent multiples of 6x (the motor has 6 poles) or possibly a center frequency at 18x (the motor has 18 stator slots) that is modulated by 6x.
28xMS, 56xMS	The motor has 28 rotor bars. 56 = 2 x 28
54xMS	54 = 3 x 18, where 3 = number of motor phases, 18 = number of motor stator slots.
84xMS	84 = 3 x 28, where 3 = number of motor phases, 28 = number of motor rotor bars.

Current waveforms were analyzed to extract motor speed harmonics and other important parameters believed to be related to fuel pump condition and performance



**Portable Computer and Data Analysis
Virtual Instrument (VI)**

TEST PARAMETERS

- | | | |
|----------------------|---------------------|----------------------|
| ✓ Month | ✓ Pump number | ✓ T1, T2, T3 (mv/A) |
| ✓ Day | ✓ Flow rate (pph) | ✓ Neutral (mv/A) |
| ✓ Year | ✓ Pressure (psi) | ✓ Test location code |
| ✓ Pump type (code) | ✓ Sample rate | ✓ Pump position code |
| ✓ Pump prefix (code) | ✓ Number of samples | ✓ DAQ VI version |

MOTOR CURRENT PARAMETERS

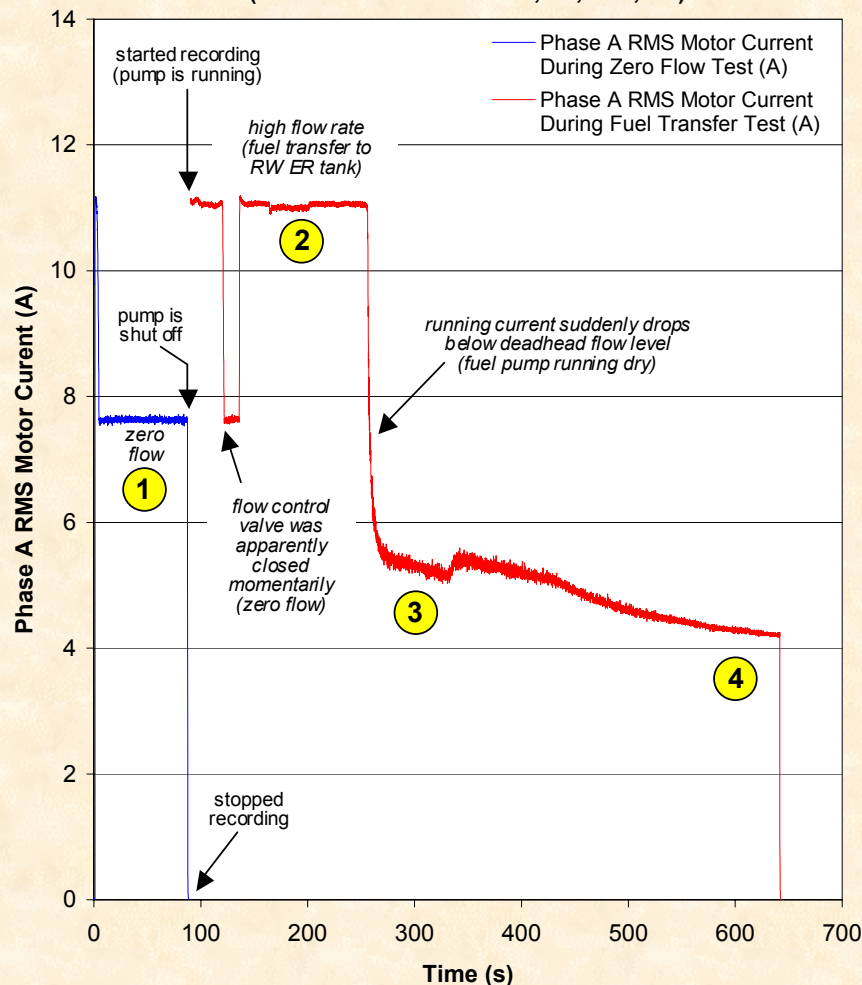
- | | |
|---|---|
| ✓ Motor speed (MS) in Hz | ✓ P3 = avg of all peaks from 28.9x to 29.1x |
| ✓ 1 x MS magnitude | ✓ P4 = avg of all peaks from 29.4x to 29.6x |
| ✓ 4 x MS magnitude | ✓ P5 = avg of all peaks from 30.4x to 30.6x |
| ✓ 6 x MS magnitude | ✓ P6* = avg of lowest 50% of peaks from 27.4x to 27.6x |
| ✓ 12 x MS magnitude | ✓ P7* = avg of lowest 50% of peaks from 28.4x to 28.6x |
| ✓ 18 x MS magnitude | ✓ P8* = avg of lowest 50% of peaks from 28.9x to 29.1x |
| ✓ 24 x MS magnitude | ✓ P9* = avg of lowest 50% of peaks from 29.4x to 29.6x |
| ✓ 26 x MS magnitude | ✓ P10* = avg of lowest 50% of peaks from 30.4x to 30.6x |
| ✓ 27 x MS magnitude | ✓ P11 = avg of all peaks from 28x to 30x |
| ✓ 28 x MS magnitude | ✓ P12* = avg of lowest 50% of peaks from 28x to 30x |
| ✓ 29 x MS magnitude | ✓ P13 = avg of all peaks from 35x to 38x |
| ✓ 30 x MS magnitude | ✓ P14* = avg of lowest 50% of peaks from 35x to 38x |
| ✓ 36 x MS magnitude | ✓ P15 = avg of all peaks from 42x to 44x |
| ✓ 42 x MS magnitude | ✓ P16* = avg of lowest 50% of peaks from 42x to 44x |
| ✓ 48 x MS magnitude | ✓ 2 x MS magnitude |
| ✓ 54 x MS magnitude | ✓ (2 x MS magnitude) / (1 x MS magnitude) |
| ✓ 56 x MS magnitude | ✓ $((83 \times MS) + (85 \times MS)) / 2 / (84 \times MS) = 1x \text{ mod of } 84x$ |
| ✓ 66 x MS magnitude | ✓ T1 phase current RMS magnitude in amps |
| ✓ 72 x MS magnitude | ✓ T2 phase current RMS magnitude in amps |
| ✓ 84 x MS magnitude | ✓ T3 phase current RMS magnitude in amps |
| ✓ Slip-poles magnitude | ✓ neutral current RMS magnitude in amps |
| ✓ P1 = avg of all peaks from 27.4x to 27.6x | ✓ current unbalance in percent |
| ✓ P2 = avg of all peaks from 28.4x to 28.6x | ✓ slip-poles based detected motor speed in Hz |
| | ✓ harmonic based detected motor speed in Hz |

* =These parameters measure the base of the spectrum. This is referred to as the "noise floor".

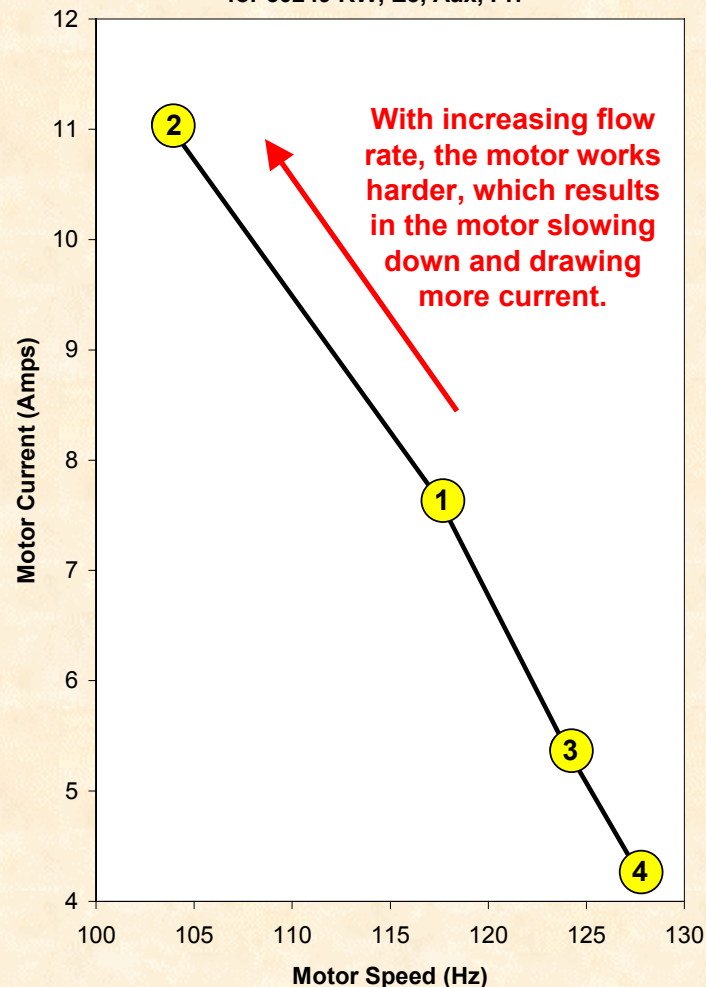
Fuel Pump ESA Parameters

Fuel pump speed and current vary according to flow conditions as illustrated by this C-141 fuel transfer test

Aux Pump Test During Zero Flow and Fuel Transfer Conditions
(Tail Number 050249: RW, E3, Aux, Pri)

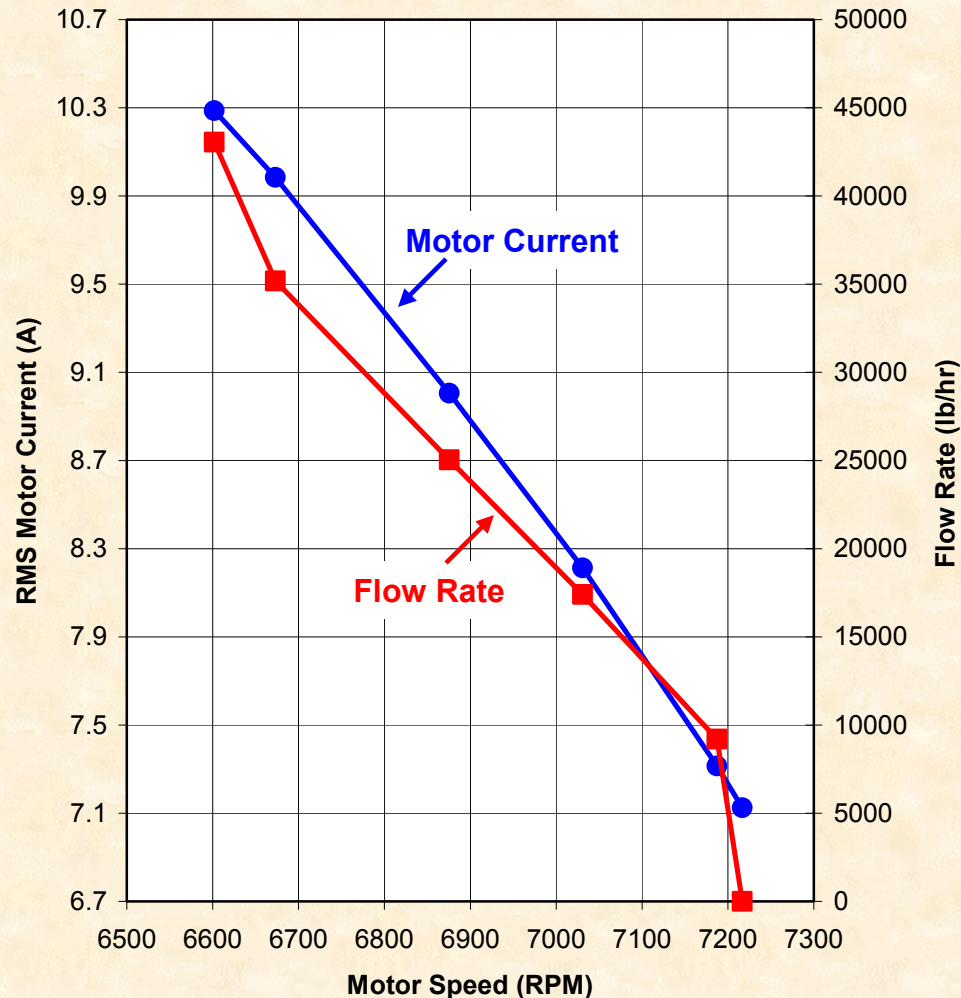
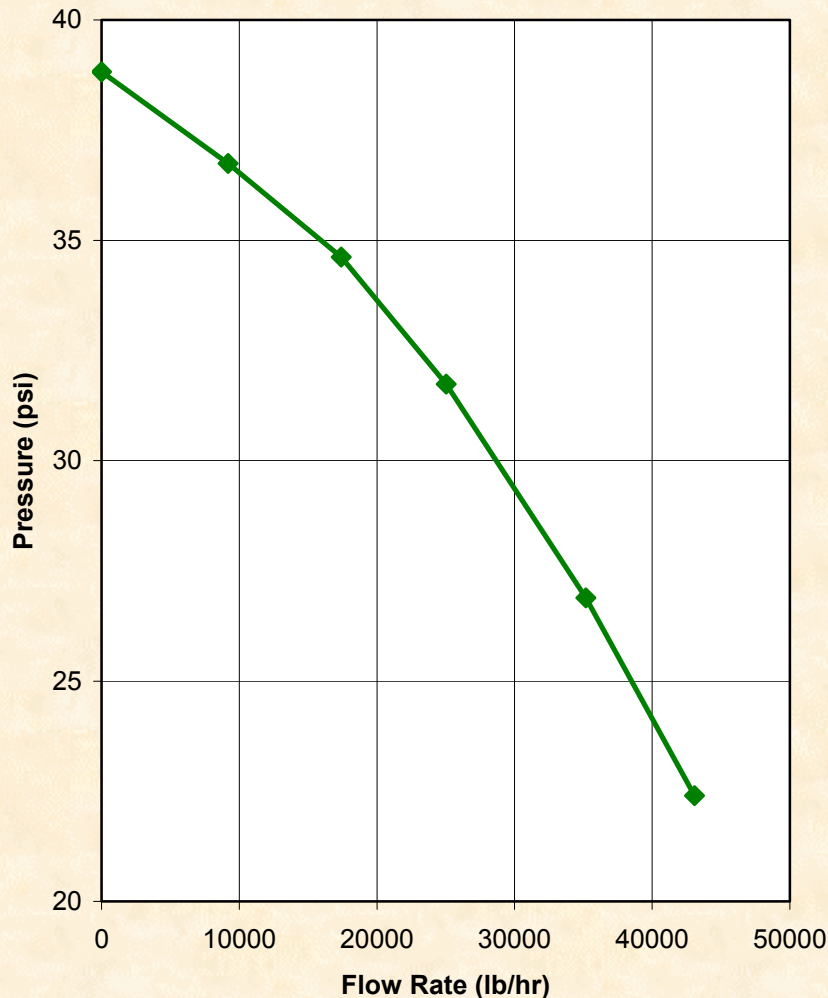


Motor Speed vs. Motor Current
for 50249 RW, E3, Aux, Pri



Using an instrumented flow test loop, fuel pump performance curves can be fully developed and studied

(Example: Auxiliary Pump, A3926, As-Received Condition)



A flow test loop also provides a means to develop diagnostic methods for detecting degradation that can adversely affect fuel pump operational readiness

The C-141 fuel pump can suffer from a variety of problems

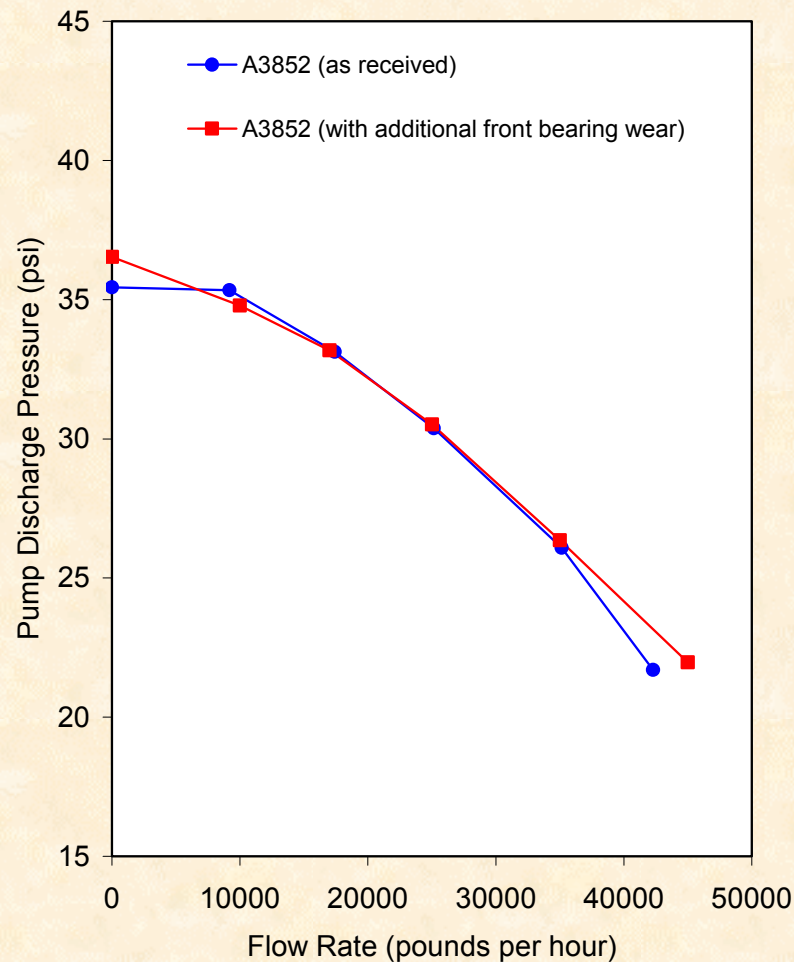
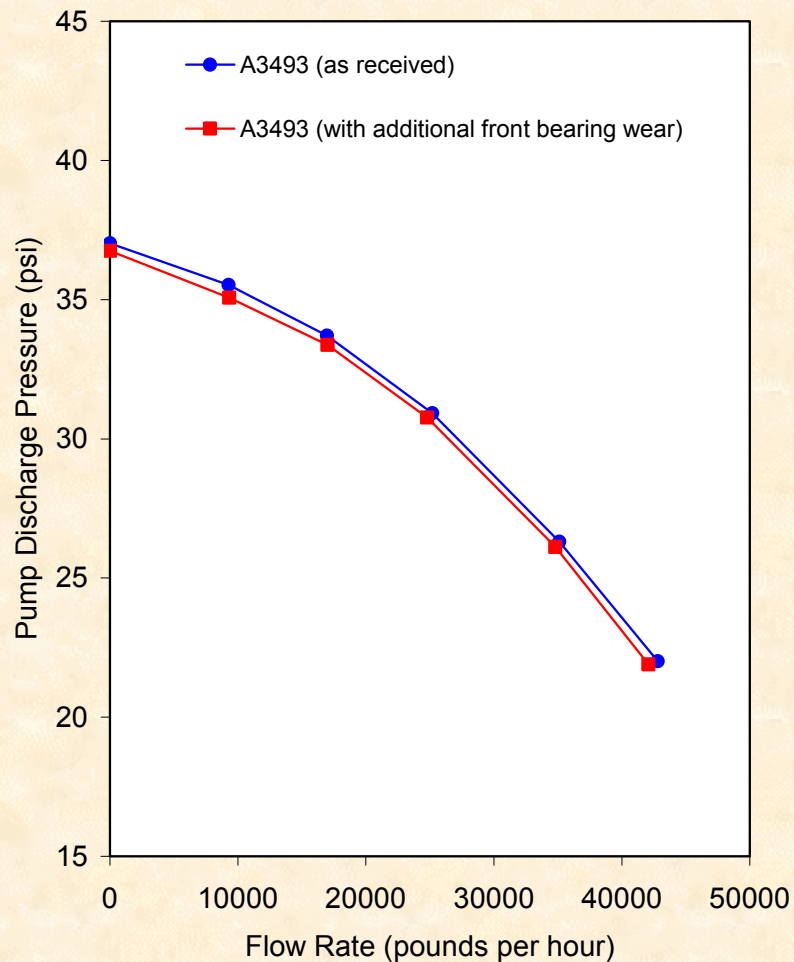
- Foreign object damage (FOD)
 - Axial thrust washer wear
 - Impeller / shroud blow by
 - Motor electrical degradation
 - Impeller imbalance due to nicks / abrasion
 - ◈ Front carbon bearing or journal wear
 - Rear carbon bearing or journal wear
- ◈ To determine if ESA methods can detect front bearing wear, five auxiliary pumps obtained from AMARC were tested in “as-received” condition and after machining an additional ~ 10 mils (0.010 inches) wear in the front carbon bearings of each pump.



Aerospace Maintenance and Regeneration Center (AMARC) at Davis-Monthan AFB, AZ

Hydrodynamic performance curves do not provide a reliable means of detecting the additional bearing wear

(Examples: A3493 and A3852)

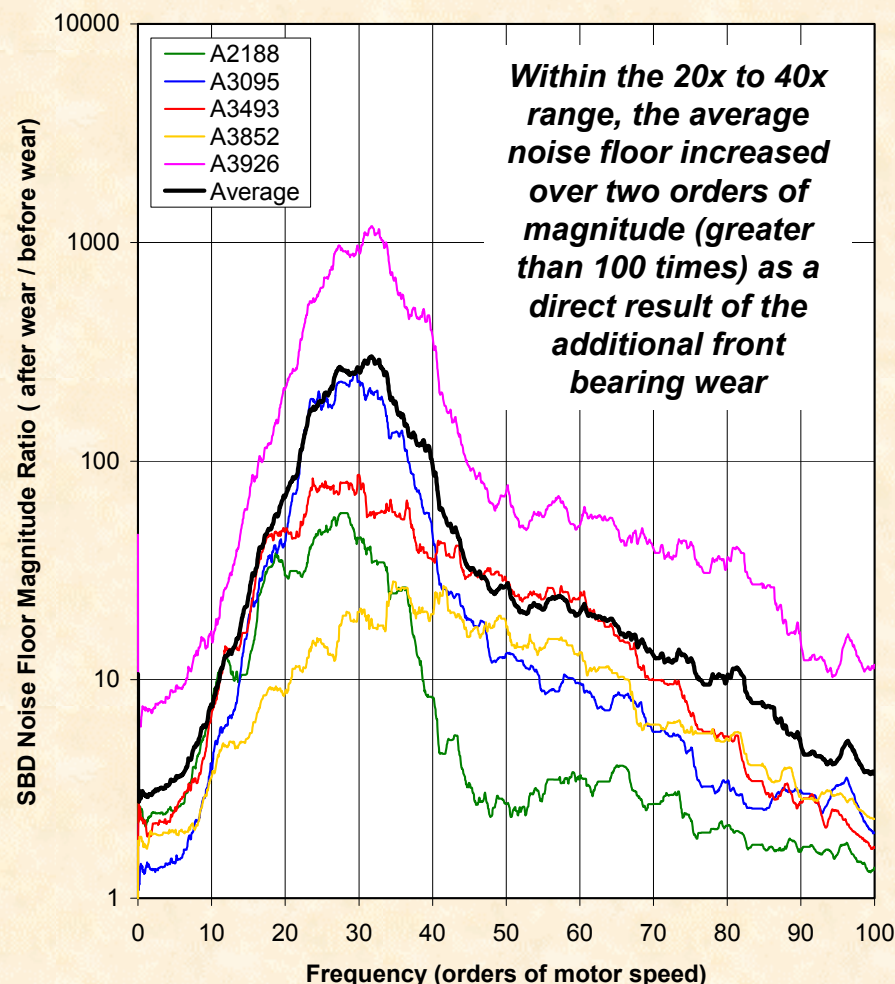
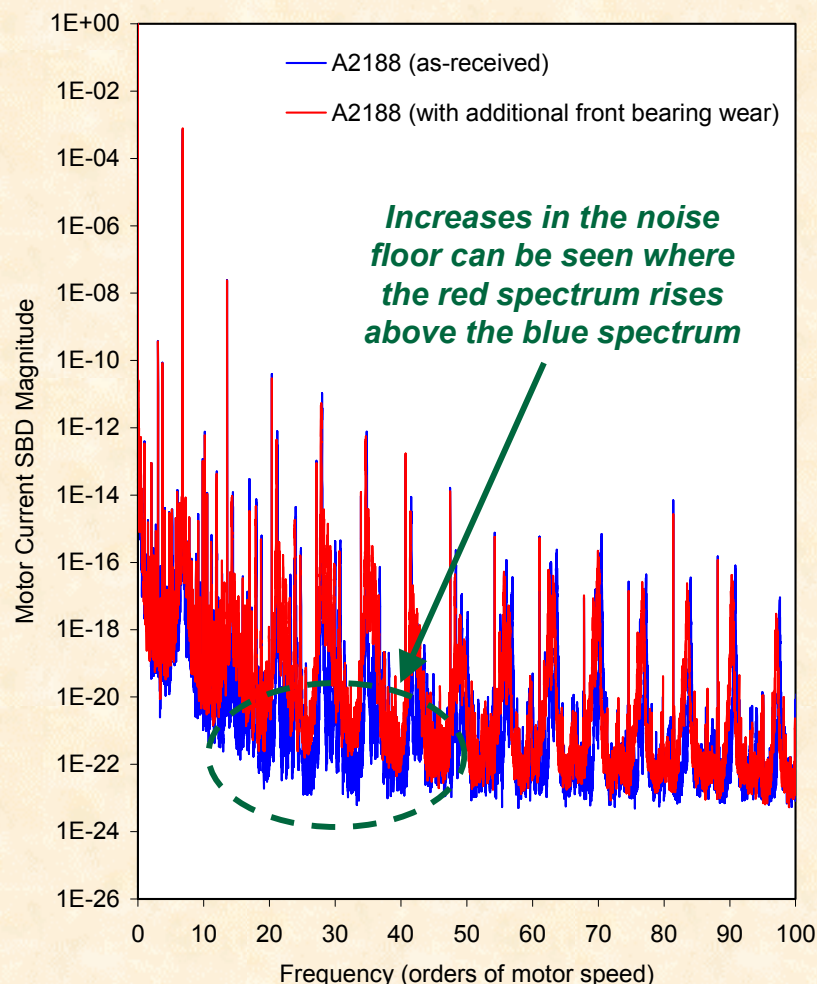


Efforts were focused on developing a new method that can quickly detect bearing wear in fuel pumps that are installed in flow test loops and in C-141 aircraft

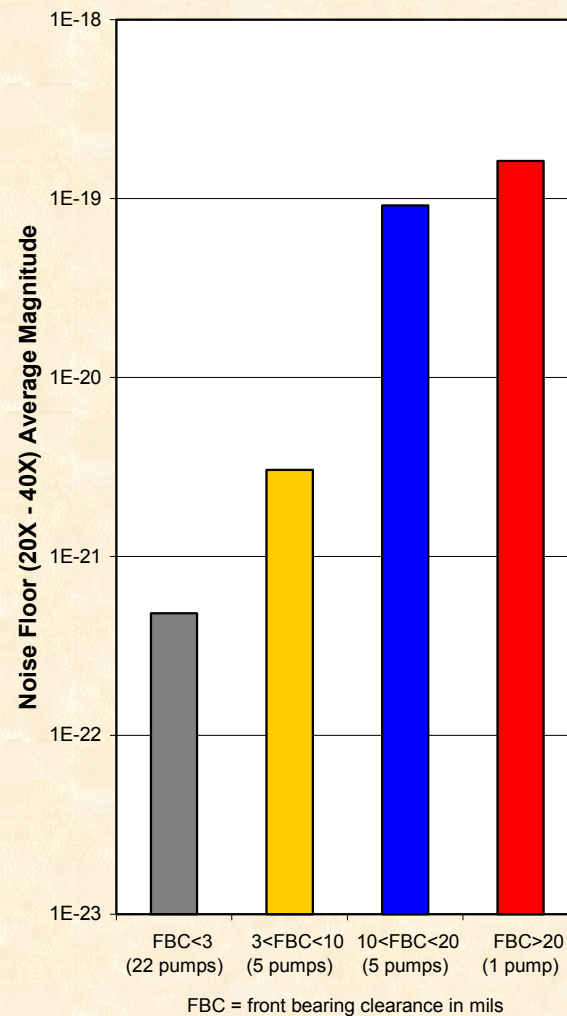
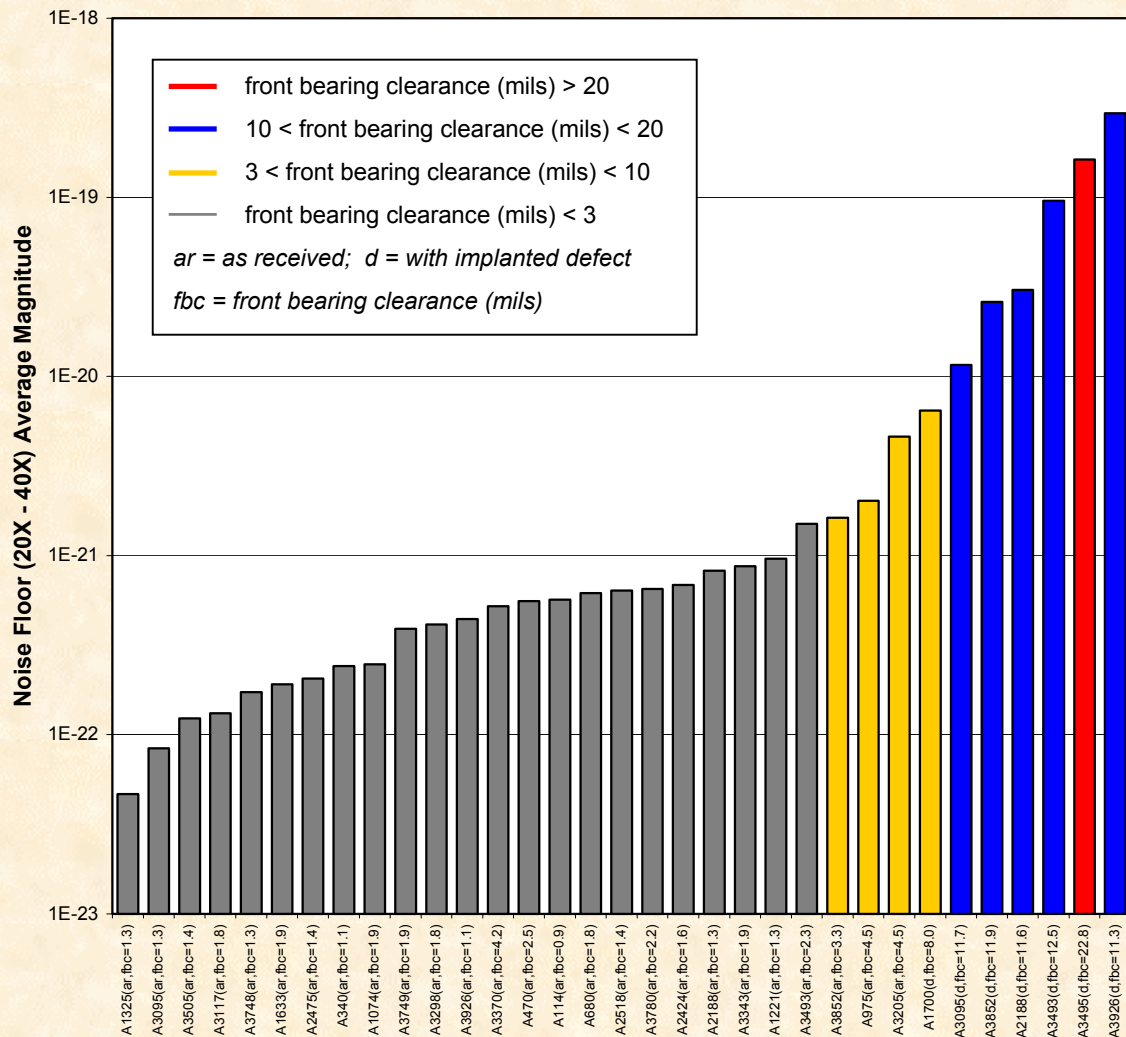
An ESA-based method that can detect fuel pump bearing wear at deadhead (zero flow) conditions would be particularly beneficial

- An ESA-based method would only require access to the motor power leads.
- Zero-flow conditions are easy to establish on an aircraft while on the ground.
- Although a significant fuel pump flow rate can be established (from tank to tank transfers), zero-flow testing is less intrusive.
- An ESA diagnostic method that can be used at zero flow is more “robust” than a method that is sensitive to flow-rate variations.

It was discovered that the noise floor of the demodulated motor current spectrum at deadhead conditions increased in all five pumps after the front bearings were degraded



When the 20x–40x noise floor magnitudes were plotted for all auxiliary pumps where the bearing dimensions were known, a strong relationship was revealed



Several activities are ongoing or planned for the near future

- Additional testing of auxiliary fuel pumps is ongoing. Methods for detecting other pump degradations using ESA will be explored.
- A comprehensive test plan will be carried out on main fuel pumps for the purpose of identifying ESA diagnostic methods for these pumps.
- A suitcase-style ESA instrument is under development. Two prototypes will be constructed and delivered to the Air Force at the conclusion of the project.
- Additional opportunities for developing ESA diagnostic systems will be explored with the Air Force and other interested organizations.

Summary

- **Electrical signature analysis (ESA) can be a powerful addition to condition based maintenance programs.**
- **ESA is a non-intrusive technology that exploits the abilities of electric motors and generators to act as transducers.**
- **ESA can enhance equipment safety, reliability, and operational readiness by providing improved diagnostics and prognostics.**
- **The Oak Ridge National Laboratory (ORNL) is presently developing a portable ESA-based instrument for monitoring the condition of C-141 fuel pumps.**
- **Fuel pump electric current data have been acquired from many pumps that were tested at Wright-Patterson Air Force Base, Oklahoma City Air Logistics Center, and ORNL.**
- **A new capability to detect front bearing wear in C-141 auxiliary fuel pumps has been developed using ESA. Additional capabilities are anticipated through continued testing of auxiliary and main fuel pumps in the field and at instrumented test facilities.**